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Original research article

Stepping on the Gas: Pathways to Reduce Venting in Household-Scale Kenyan Biogas Digesters

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ABSTRACT

One method of producing bioenergy is through Anaerobic Digestion (AD) of plant, animal, and human waste in a biodigester. AD is a cost-effective method of simultaneously managing harmful waste, creating biogas for cooking, and producing nitrogen-rich liquid fertiliser for agriculture. However, there is minimal exploration around how these household-scale biogas digesters, in Kenya and beyond, contribute to global bioenergy methane emissions - this paper directly addresses this gap.

We employ a two-phase approach which establishes the scale of the challenge through a rapid review of available literature on loss, leaking and venting, then contextualise this data with the lived experience of 33 biogas-users across 5 counties in Kenya.

The results highlight three critical dimensions - the demand, supply, and systemic from the users' perspectives - all linked to the venting phenomenon. The demand side showed a lack of understanding of venting and its causes, these included; pre-processing feedstock, feeding regime, seasonal influence, pressure, cookstove stacking, lack of maintenance and market access. On the supply side, our critical learning highlighted that biogas units are typically sold based upon the available feedstock, rather than the potential gas need. Next, we identify the systemic drivers; household-scale digesters do not pose a climate threat, a lack of technical solutions, and the overwhelming Pandora's Box of impacts. For each driver - the supply, demand, and systemic - we highlight a series of mitigating actions that small-scale, locally-led biogas stakeholders can take to minimise venting, this is summarised in our practical "venting framework".

1. Introduction

"*Methane is the primary contributor to the formation of ground-level ozone, a hazardous air pollutant and greenhouse gas, exposure to which causes 1 million premature deaths every year. Methane is also a powerful greenhouse gas. Over a 20-year period, it is 80 times more potent at warming than carbon dioxide*"

[1]

1.1. Household scale biogas

One method of producing bioenergy is through Anaerobic Digestion (AD) of plant, animal, and human waste in a biodigester. AD is a cost effective method of simultaneously managing harmful waste, creating biogas (primarily methane and carbon dioxide) for cooking, and producing nitrogen-rich liquid fertiliser (digestate) for increasing agricultural yields [2,3]. AD can be conducted across multiple scales, owned and managed by national governments, regional organisations, or individuals, and implemented as a method of both energy production and consumption [4]. In this paper we focus on household-scale biodigesters, with a capacity between 8 and 12 m^3, primarily operated and owned by the user of the outputs (gas and digestate) - these household scale digesters broadly fall into three categories fixed-dome, floating-dome, and bag type digesters, all of which have their unique challenges

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[5–7] – in this paper we only consider fixed-dome and bag type digesters (Fig. 2 and Fig. 3). As a critical component of UN SDG7 - energy for all [8] - household scale digesters have been promoted across the globe through large-scale biogas programs e.g., Nepal Biogas Support Program (1992–1997, 1997–2003, 2003–2009), Vietnam Biogas Program (2003–2012, 2013–2017), Indonesia Domestic Biogas Program (2009–2012, 2012–2019), Africa Biogas Partnership Program (2009–2013, 2014–2018), Africa Biodigester Component (2020–2025), and India's National Bioenergy Program (2022–2026). Nevertheless, despite these large scale programs a significant number of challenges remain with the global implementation of household-scale biodigesters [9–11] which has slowed the mass-adoption of these technologies.

1.2. Global methane emissions

As illustrated in the quote which opens this paper, methane emissions are the second most significant contributor to the destabilisation of our global ecosystem. Since the industrial revolution, methane is responsible for 30 % of the rise in global temperatures [12] despite only having an atmospheric lifetime of 12 years, compared to hundreds of years for CO_2 [1]. Currently, the global energy sector (oil, natural gas, coal and bioenergy[1]) account for 40 % of methane emissions from human activity, this is second only to the agriculture sector [12] - Fig. 1 shows the breakdown of these emissions by sector. Whilst venting and flaring are documented across the gas pipeline, offshore gas, offshore oil, and onshore oil sectors, is it not in bioenergy sector (defined as solid bioenergy, liquid biofuels and biogases [12]). In addition, there is minimal exploration of how household-scale biogas digesters contribute to global bioenergy methane emissions despite their being an estimated 50 million household scale biogas units globally as of 2019 [4]. Whilst, the Voluntary Gold Standard (VGC) and Clean Development Mechanism (CDM) carbon credit methodologies for biogas do assume up to 10 % methane leakage from the digester depending on construction type of the digester, there is no distinction between different types of methane losses and this number is largely standardised across all different use cases [13]. These are critical considerations for the completion of SDG7.

When considering the **intersection of household-scale biogas systems and the associated methane emissions** we define these losses through two categories, leaking and venting - in this paper we focus directly on the under-studied phenomenon of venting. Venting is the controlled release of biogas at certain pressures (as the total capacity of the digester is reached but the production of gas is a continuous biological process), whereas leakage is the uncontrolled release of biogas usually due to defects in the biogas digester, fittings, or appliances. For example, the valve to the stove can rust and then stop functioning. Fig. 2 and Fig. 3 illustrate the different venting processes for fixed-dome and bag-digesters respectively. For fixed dome digesters (digesters which are typically made from bricks and concrete and buried underground) the design of the main gas dome and outlet chamber determine venting pressure. As the gas volume increases, so does the pressure in the dome placing the dome under tension. If the gas pressure is greater than the compression forces (from the concrete structure and soil on top) on the dome then cracks could potentially appear - especially due to the simple construction of these domes (with no concrete, or reinforcement). This failure point is typically ~8 kPa, hence fixed-dome digesters are designed to vent at 8 kPa and above [14]. The pressure is determined by the difference in height between the throat in Fig. 2 and the outlet; for example if the throat height is 80 cm the venting pressure is 8 kPa [14,15].

For a bag digester, essentially a long plastic bag, the maximum pressure is determined by the strength of the plastic or fabric, the joints and/or fittings, this varies across manufacturers and is typically around 2 kPa (maximum 4 kPa) - which is a significantly lower pressure than the fixed-dome units. Excess pressure is often released through a U-bend shown in Fig. 3. A U-bend is attached to the pipework close to the digester and before any valves (so the safety release venting valve cannot be accidentally turned off). The U-bend is filled with a solution, typically water, and thus behaves as a simple manometer - 20 cm of water results in 2 kPa of pressure for gas to escape past the water head.

1.3. Biogas systems in Kenya

The Government of Kenya has steadily constructed a robust and facilitating policy and regulatory framework that bolsters the progression of the biodigester initiatives. In 2012, Kenya joined the sustainable energy for all (SE4All) initiative, in 2015 developed an action agenda [16] and investment prospectus [17], and in 2016 ratified their part in the UN SDGs. In addition, the Energy Act of 2019 [18] delineates the responsibilities of both the National and County Governments regarding energy, and outlines the execution of the bio-energy agenda which encompasses bio-digesters. In conjunction with the act, the National Energy Policy of 2018 [19] outlines concise intermediate and long–term tactics for incorporating biogas into sustainable energy planning. In 2020, the government unveiled the Bioenergy Strategy [20] as a blueprint for fostering and propelling bioenergy as a formal sector that can serve as a catalyst for Kenya's economic growth and, in addition, stated a reduction of GHG emissions by 32 % by 2030 in Kenya's first NDC commitment (linked to the Paris Agreement) [21]. However, there is still a lack of emphasis on directly promoting biogas for emission reduction.

International large scale biogas programs also look to push forward the Kenyan sector. The Africa Biogas Partnership Program (ABPP) has influenced the adoption of over 22,000 biodigesters across the country between 2009 and 2019 [22] and by 2030, household biogas use is projected to reach 0.8 % nationally [20]. In 2021 the Africa Biodigester Component project (ABC) [23] replaced ABPP and is targeting the construction of 20,000 systems by 2025 by encouraging sustainable biogas market growth. Across Kenya, the key barriers for adoption are around technology affordability and access to finance for biogas companies [23]. The core of the biodigester potential is from dairy cows kept in stables; there are 939,916 households rearing 2,209,980 dairy cows [23].

1.4. Aims & objectives

In this paper we aim to understand, explore, and establish pathways to minimising venting in household-scale, user-owned, biogas digesters. We employ an approach which establishes the scale of the challenge through a rapid review of available literature and contextualise this data with the lived experience of biogas users, experts, and global stakeholders. Our core aim is realised through three key research objectives, which are to:

- draw on other publications to **understand** the scale of the venting phenomenon.
- **explore** the demand, supply, and ecosystem side drivers of venting through detailed qualitative interviews with household-scale biogas unit owners drawing on socio-cultural, behavioural, and technical perspectives.
- **establish** a “venting framework” (or pathway) which enables household-scale, locally led biogas stakeholders to establish optimisation programs which minimise venting at the lowest cost.

1.5. Novelty & significance

The novelty of this paper is in its focus on venting in household-scale biogas digesters in Kenya. Existing research focusses on larger scale systems under the guise of “small-scale”, for example Diaz Huerta and Bose [24] state their focus is “small-scale” digesters and yet they

[1] This does not include any data for household-scale biogas digesters.

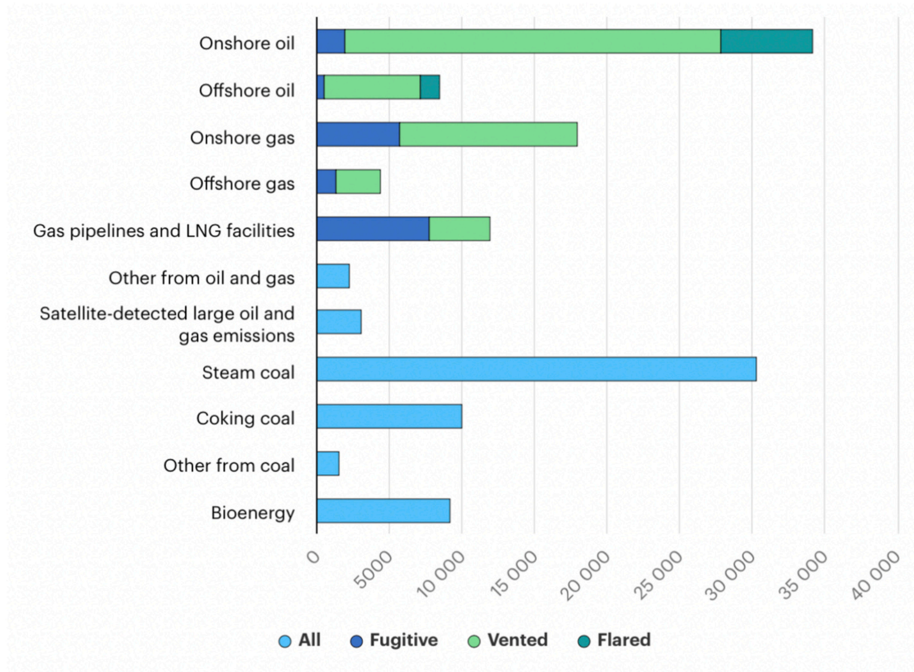

Fig. 1. World methane emissions from energy sources (kt), IEA estimate [12].

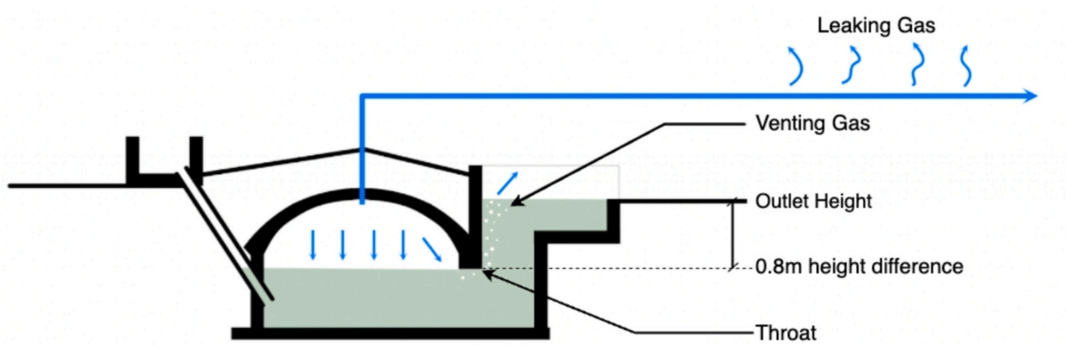

Fig. 2. Fixed dome design considerations and their effect on leaking and venting (produced by authors).

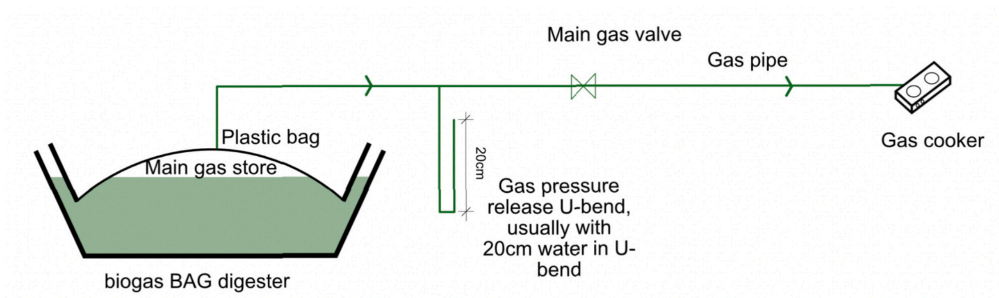

Fig. 3. Venting mechanism in a generic bag digester using a U-bend/Manometer (produced by authors).

consume feedstock from 185 cows daily (compared to 2 cows as per the farmers in this study). This results in the biogas systems which provide the standards for 'loss' being based in Europe and operated in a commercial setting [24–26]. This is a significantly different use case to a rural or peri-rural farmer in Kenya or indeed across sub-Saharan Africa. The different in context and use case, not only highlights the disconnected nature of these existing studies (when learnings are inadequately applied to East and sub-Saharan Africa) but additionally a systemic issue of the wider "development" sector applying Eurocentric models of development that overlook and disregard the lived experience of "less developed" nations [27,28]. Moreover, as highlighted by Scheutz and Fredenslund [26] there is a lack of clarity around what constitutes and drives methane losses. Thus, the distinction we make in this paper between leaking and venting is significant as it differs from the "state-of-

the-art" VGC and CDM carbon credit methodologies that much of the biogas literature relies on, which use the word leakage to encompass both leaking and venting. For example the VGS states "The physical leakage from biodigesters is calculated as 10% of the maximum methane producing potential of the manure fed into the management systems implemented by the project activity" [29] whilst, CDM states "project emissions due to physical leakage of methane from biogas digesters are estimated as 10 per cent of the maximum methane-producing potential of the manure fed into the management systems implemented by the project activity" [30]. The impact of including venting in the carbon definitions opens the possibility of misreporting (in both over and under reporting) methane emissions and is significant for the efficacy, transparency, and credibility of carbon methodologies. Within the outlined biogas literature, this paper provides the foundational work for directly addressing venting at this scale within the Kenyan context and connects the lived experience of Kenyan farmers to the phenomenon of venting. This is supported by a comprehensive qualitative data set as well as an additional quantitative publication [31]. Thus, its significance is in closing the research gap outlined above and providing compare comprehensive understanding of the drivers of this unique phenomenon from the perspective of the end-users of biogas systems who use these systems to directly support their livelihoods.

1.6. Structure of paper

The structure of the paper is as follows; the next section outlines the methods and our two-phase approach. Phase 1 includes a rapid review of household-scale biogas systems, user-behaviour, leaking and venting, and limitations to this approach. Phase 2 outlines the qualitative research methods for data design, collection, transcription, analysis, writing as well as several additional specific limitations. The findings section presents the lived experiences of Kenyan farmers around venting (with integrated results from the rapid review) divided into three sections – the demand, supply, and systemic drivers of venting. The discussion and synthesis section provides a series of actions to minimise venting based on the demand, supply, and systemic drivers. In addition this section brings together all the findings into a thermotical framework for minimising venting. The paper finishes with a conclusion containing the key messages and potential future areas of focus.

2. Methods

This section presents our two-phase approach to understanding demand, supply, and systemic drivers of increased venting in household-scale biogas systems. First, we conduct a rapid review of household-scale biogas systems, user-behaviour which influences system functionality, and any existing literature on leaking and venting in these household systems (phase 1). Second, phase 2 presents the core of this section - the qualitative design, data collection, transcription, analysis, and limitations linked to this approach.

2.1. Phase 1 - rapid review: household-scale biogas systems, user-behaviour, leaking and venting

Rapid reviews are designed to identify relevant grey and published literature in time-limited research settings. As defined by Tricco et al. [32], rapid reviews are "a type of knowledge synthesis in which components of the systematic review process are simplified or omitted to produce information in a short period of time". This method enables researchers to effectively narrow the field of focus, and in specific cases where the literature is underdeveloped - such as the AD literature in the International Development sector - identify the majority of relevant key literature in a timely manner. This approach was comparably used by Hewitt et al. [10] for the household-scale biogas plant failure literature - a similarly narrow field of scope.

Given the overlooked nature of biogas systems and services when compared to other energy sub-sectors within the energy access (or SDG7) and/or the international development space (such as in the solar PV or Improved Cookstove sectors) [33–35], there is significantly less grey and published literature which would be relevant to this paper. We used combinations of search terms such as (but not limited to): household-scale biogas systems, leaking, venting, loss, and user-experience within ScienceDirect [36] and others, further leveraging AI search tools – such as connected papers – to identify prior, derivative and thematically connected papers, ensuring that no data was missed in this search. We additionally leveraged authors' extensive knowledge of the existing literature base and further focussed our search by only addressing studies that: had a focus on the household-scale biogas sector, had an element which engages with user-behaviour around biogas system operations, directly addressed leaking and/or venting. The results of this rapid review are integrated into the findings section and, where relevant, used in support or contrast to the presented user-behaviours. This is especially the case in the systemic drivers of venting.

2.1.1. Limitations

Rapid reviews have several limitations especially around transparency and reflexivity [37], in the case of this paper we have looked to mitigate against this by providing a detailed outline of the literature search process as well as providing other examples where robust rapid reviews were conducted. In addition, rapid reviews can be limited by unconscious bias and the positionality of the researchers, often from the European (and UK) perspective [38]. An active decision in this work was to conceptualise, write, and review with authors from both the UK and Kenya (i.e. the academic institution and project partners), within this process we have discussed and reflected on this bias, looking to mitigate it through diverse perspectives which are often not considered by European academics working in "development projects". Finally, rapid reviews may not capture the most elusive and obscure literature. The authors of this paper have published extensively in the biogas sector as well as having significant technical and practical implementation experience hence we have looked to mitigate this limitation through author experience [10,31,39–43].

2.2. Phase 2 - evidencing lived experience: qualitative methods

2.2.1. Data collection design & implementation

Between the 21st of November and 1st December 2023, African Biogas Program Limited (ABPL), with expert guidance and advice from the University of Nottingham, conducted 33 qualitative interviews with a diverse group of biogas owners and users, typically farmers who own their systems, used the gas for cooking, and the digestate for various forms of fertilisers (direct application, foliar feed, and in composting). These interviews were conducted across five counties surrounding Mt. Kenya - Kiambu, Muranaga, Nyeri, Embu, and Meru Counties. These counties were chosen as they see typically elevated rainfall, rich soils, and high levels of solar radiation resulting in dense clusters of smallholder farmers with a primary or secondary income being generated through the sale of crops and animals. Additionally, these five counties represent significant clusters of biogas digesters installed by the ABPP and ABC programs which make up the majority of biogas digesters installed in Kenya [22,23,44] and through which ABPL has the majority of their 22,000 customers. The 33 farmers were selected with criteria including; experiences with their biogas systems, uses of biogas and bio slurry, size of system, accessibility (reachable by vehicle), inclusion in biogas farmer groups, experience with national biogas programs, and new biogas technologies (such as IoT enabled smart meters [39]). However, whilst options were presented to university researchers, the

final decision was with ABPL who have deep and rich experience within the Kenyan biogas sector as the coordinator of the national government biogas program.

The interviews were primarily conducted by ABPL county coordinators who provide regular technical support to the farmers.[2] Eight county coordinators conducted the 33 interviews, building on their preexisting relationship with the farmers to ensure the efficacy and quality of interviews. Taking a phenomenologically inspired approach [45] focussed on the lived experience of the farmers and their experience of biogas systems and wider services, these interviews were based around a semi-structured interview guide that was co-created by ABPL, the University of Nottingham, and Inclusive Energy. This guide was used to prompt discussions with a range of topic areas with one of the main focuses on understanding the phenomenon of venting. There were no set questions, only prompts, as these discussions were participant-led and based on the interests and priorities of the participants. Thus, reflecting the participants needs rather than the interviewer's priorities. This means that depending on the flow of the interview and the types of participant experiences, certain topics were not covered in every interview. The data collection design and implementation was approved by the ethics board at the University of Nottingham and complied with all data protection and privacy requirements.

2.2.2. Data transcription, analysis, and writing

One core output of the *Smart Biogas 3: Digesting Data* project is the transfer of research skills and experiences between the academic and non-academic partners. The transcripts were analysed by the county coordinators using a two-step approach. First, inductive thematic analysis to extract the key themes for groups of transcripts - one country coordinator developed one analysis framework for around four interviews (that they did not conduct or transcribe). We chose this approach, to further disconnect the interviewer, with the transcriber, with the analyser, to further increase the robustness of the data and ensure that any issues with translation or meaning were mitigated (most interviews were conducted in the local language or a mix of local language, Swahili, and English). Second, the county coordinator-generated analysis frameworks were compiled - eight in total - to further refine the key themes into one final analysis framework. This process was done for the entire data set with themes relevant to specific papers - in this case venting - extracted for the writing process. The themes, which were generated inductively from this process, that were particularly relevant to venting related behaviours were (sub-codes in brackets): *AD System General* (Abandonment, Bad Practice, Challenges & Solutions, Digester Type Comparisons, Feedstock & Feeding Regime, Optimisation, Post-Sales Support, Reason for Purchase, Safety, Seasonality, System Upgrades, Training), *AD System Gas* (Gas Pressure, Use of Excess Gas, Use of Gas), *AD System Digestate* (Use of Digestate, Use of Excess Digestate), *AD System Leaking and Venting* (User perceptions of Venting), *AD System Delivery Models* (Cooperative/Farmers Group, Maintenance Service, Savings from Biogas), *Alternative Fuel Use* (Lack of Biogas Functionality, Multiple Hobs, Time, For Specific Fuels).

The county coordinators each wrote a piece of analysis based on their interview framework and transcripts which makes up the core component of this paper. The University of Nottingham researcher provided technical assistance across this process to ensure the robustness of the transcriptions and analysis, highlighting any mistakes or missing information.

2.2.3. Limitations

As with any research with human participants there are a number of general limitations associated with phenomenological approaches and participant-led interviews, these include participant bias, subjectivity in data interpretation, the time it takes to collect data [45,46], which we mitigated through a meaningful participatory and co-designed approach. There were several limitations which were directly linked to the methodological approach of the paper, which had the potential to affect the quality of outputs. These included outsider status, bias, and positionality [38], the role of language, and training ABPL county coordinators - Table 1 outlines how these were mitigated.

Table 1
Mitigations for specific qualitative interview limitations.

Outsider Status	We looked to mitigate outsider status by spending an extended amount of time with participants, sharing food, and building on the previous relationships established by the county coordinators - blending insider and outsider approaches [47]. In some cases, the presence of the University of Nottingham researcher was directly referenced as being beneficial for the outcomes due to it creating a more formal framing (or special occasion) for the participants. In addition, some interviews were conducted solely by county coordinators with the University of Nottingham researcher not present, this did not affect the quality of the interviews.
Bias and Positionality	County coordinators are normally the ones providing the information, customers are usually the ones asking the questions. The qualitative interviews required a redefinition of this power. I.e. customers asked the questions. This process was challenging for both county coordinators and customers. Similarly, the interviewees may have been confused about why we were interviewing them about their biogas units, as they have had them so long and the county coordinators are the experts in this topic area.
Language	County coordinators were trained on semi-structured qualitative interviews in English, but mostly practiced in their own language which, whilst made the participants more comfortable, it also made it difficult for training county coordinators - this means that the quality of the interviews was dependant upon open communication between University of Nottingham and ABPL. Reflective sessions between interviews then became the critical element for training.
Training	Interviews started being very short (less than 10 min), but subsequently increased in time, up to 1 h, by the end of the day with each county coordinator. This didn't include the 10/15 min of introductions and project explanations. Still improvement was needed in shaping the responses into a conversation rather than a survey or questionnaire. County coordinators were more used to the traditional survey style of data collection.

3. Findings

Throughout this section we present the demand, supply, and systemic drivers of venting – demand-side is associated with actions which user's take that contribute to venting, the supply-side captures the actions of manufacturers, distributors, and suppliers of biogas systems, whereas the systemic addresses the surrounding ecosystem (accompanying systems and services and enabling environment) – this broadly echos Practical Actions systems approach to energy projects through the Participatory Market Systems Development toolkit [48]. Through the demand-side we highlight how user awareness and behaviour patterns drive increased venting. On the supply-side we explore the effects of digester sizing (from the user perspective) and the sales practices of biogas manufacturers and builders. In the systemic section we broaden the focus beyond the techno-economic to understand how the wider system affects venting. Finally, we synthesise these results and assign a potential venting risk to enable practitioners to more effectively identify key programmatic areas in which to minimise venting.

3.1. Exploring demand-side drivers: awareness and behaviours

Venting is under-studied and often misunderstood. This translates beyond the academic, practitioners, and policymakers to the users and

[2] In addition, this ensured that county coordinators at ABPL both gained qualitative research skills and were journal paper authors - a critical wish in their professional development.

owners of these systems who have never heard of the phrase "venting". It becomes challenging for users to talk about their lived experience of a phenomenon when the word itself is new to them. The complexity of this phenomenon is increased as the users think they do not have a way to understand if their units are releasing gas (through venting or leaking). AD systems are essentially black boxes from the user perspective. In reality, users may be able to see bubbling digestate in the expansion tank and bubbling through the U-Bend, but this required training to identify:

> "*But the bottom line is that it is good when it is producing gas. We have no ability to know whether it is enough or not enough*"
>
> (*K-Em-2*)

3.1.1. User awareness of venting

Typically venting occurs when more gas is produced than used, often independently of digester size (as the rate of gas production is broadly similar in all digester sizes), and, for the majority of cases, presents itself as the perception of extra gas or always having enough gas for their needs. However, when participants were asked "How do you know the amount of gas in the system?" many responded with the same sentiment as K-Me-3, "*I don't know. When it goes off, is when I know it is finished*". Even though some have a pressure gauge (which can be a proxy for volume of gas) there is still a significant knowledge gap.

When presented with the question **- Do you have extra gas? (as a proxy for understanding venting) -** responses could be broadly classified into three categories, a) users who do not have enough gas resulting in stacking of multiple cooking technologies based on biogas availability, b) users who only needed to supplement their biogas for large events and family gatherings, and c) users who have enough gas for all their needs (i.e. it has never run out). The reality for many users is that they haven't considered the question of extra gas, as illustrated by this contradictory statement from one participant, "*I do not have excess gas but I have enough for all my cooking needs at all times, and when I have excess I normally use it to boil water*" (*K-Ny-1*) – signifying a difference between gas that is wasted and gas that is additional but utilized. However, several users understood the link between pressure, feeding, and excess gas. K-Ki-4 highlights their perceptions:

> "*If I happen to notice that the gauge is showing that the gas is excess, indicating danger, I can cook something like githeri,* (*mixture of maize and beans*) *or if I had planned to cook rice, I will shift to cooking chapatti so that all the excess gas can be utilized quickly, I wouldn't want such a thing causing any issue for the biogas because I can't just release the gas into the atmosphere. I remember we were told during our training that releasing such gases without utilizing them into the atmosphere have dire consequences and will destroy the environment.*"
>
> (*K-Ki-4*)

3.1.2. User behaviour which effects venting

The specific areas of user behaviour identified in the interviews as effecting venting are; pre-processing feedstock, feeding regime (linked to seasonality), pressure, cookstove stacking, lack of technical training on general maintenance and venting, and lack of market access.

3.1.2.1. Pre-processing feedstock. The pre-processing of feedstock, i.e. the treatment of feedstock before it is placed in the digester, reduces the 'digester shock' of introducing new material [49]. This was additionally outlined by the practical experiences of one country coordinator, "*then if you leave your dung in the mixing chamber and you release it later into the digester when it is already hot, it also stimulates the activities of the microbes*" [*project partner county coordinator*]. This makes it especially important to pre-processes feedstock to improve the quality and quantity of outputs, this could be through solar radiation [50,51] (also suggested by the county coordinator) or co-digesting multiple feedstocks [52] - in this case cow dung and food waste. The optimisation of digestion will result in the faster production of biogas (and digestate), the following effects on venting depend on the existing gas usage.

3.1.2.2. Feeding regime & seasonality. The feeding regime sits across three categories; overfeeding, underfeeding, and correct feeding - each has its own indicators as outlined by Chaney et al. [31]. **Overfeeding** results in a decreased hydraulic retention time, reduced space for gas, and thus digestate being pushed out of the digester in a semi-digested state resulting in digestion continuing outside the digester - presenting a bubbling digestate. Table 2 outlines a typical process of overfeeding which was shared by many farmers as part of the interview process - an active decision to overfeed the digester in order to generate more digestate (for direct application, composting, or foliar feed) and then return to the advised feeding strategy after this time-period of an increased need for digestate was completed. This seasonal use-case linked to over feeding is recognised by participants, one participant talked of not having enough gas, but "*I am actually not complaining, we actually feed on a daily basis because we need a lot of slurry to make manure*" (*K-Em-2*).

In addition to the seasonal influence of the use case outlined above, i. e. overfeeding to produce more digestate in planting season, the farmers identified two additional dimensions which are affected by season - rain and temperature. A wetter environment requires an adjusted feeding ratio to ensure consistent digester performance (i.e. wetter feedstock requires less water in mixing). In addition, many participants feed daily in rainy seasons "*so that the dung is not washed away by rainwater*" (*K-Ny-2*) often resulting in additional overfeeding - both of which affect the production of biogas. Second, temperature changes affect the microbial processes within the digester, "*During rainy and cold seasons noticed low pressure and during hot seasons the pressure is very high*" (*K-Ny-1*), however, participants did not often change the feeding schedule, thus are overfeeding in cold seasons and underfeeding in hot seasons - which has a significant effect on venting. Additional work as part of the SB3 project explores the full implications of seasonality. The complexity of feeding regime increased due to changing livestock numbers across seasons. When increasing (or decreasing) the number of cows or livestock, farmers were keen to use all the available feedstock as a way of managing their entire waste stream (so a second process for waste management was not needed), despite realising the potential for overfeeding.

Intentional **underfeeding** was typically not an issue for participants, only in one case did we see intentional underfeeding. This was due to the "destocking" of livestock resulting in a lack of feedstock and a desire to keep the AD system producing gas and digestate. Underfeeding or irregular feeding may cause the digester to cease functioning [10].

In the case of the correct **feeding schedule for the digester size**, venting occurs simply when more gas is produced than used (often due to the oversizing of units when compared to the need for gas - this is further explored below in the supply-side drivers). Feeding schedules in this case were based on; the pressure gauge - feeding is a reaction to a low pressure on the gauge - "*because the moment I notice that the gauge is below a certain amount, I immediately get to it* [*feeding*] *and do the necessary, that's why it's always almost full*" (*K-Ki-4*), and experimentation around what maximised gas production, "*Normally we feed it* [*with only chicken droppings*] *twice a week but when it is in high use, when there are many cooking needs, we feed it thrice a week when we are using the brooder*"

Table 2
A typical conversation with farmers around feeding schedule and volume.

Interviewer	How many buckets of cow dung do you feed in a day?
Participant K-Me-1	I normally put two wheelbarrows because I am in need of bio slurry which is more than the required feeding.
Interviewer	How many buckets of cow dung were you told to be putting?
Participant K-Me-1	Two buckets of cow dung mixed with two buckets of clean water

(*K-Em-1*).

3.1.2.3. Cooking pressure. Across the participants there was a clear preference for higher cooking pressures. One participant (with a bag type digester - K-Ki-2) - extended the height of the outlet pipe with the aim of retaining more digestate, increasing the gas pressure, and to be able to control when the digestate is released. This same participant also stated that there was not enough gas for cooking. The reality is that this participant has, by blocking the release of digestate, reduced the volume of available space for gas and, as bag type digesters vent at their maximum pressure, not increased the pressure of the gas but reduced the available gas for cooking. The black box nature of AD systems has resulted in this participant trying to solve their issues but ultimately resulted in compounding them. In addition, with bag type digesters, there is a perception that higher pressures will lead to a failure of the bag - resulting in users being more aware of their cooking pressure and looking to actively manage it (and often minimising venting). As one participant stated, "*tube and plastic system get damage very fast due to gas and poor fittings and when gas is excess it usually burst off thus unable to produce any gas*" (K-Mu-3).

3.1.2.4. Cookstove stacking in relation to specific food types. The stacking of multiple cooking technologies is a well-documented phenomenon and a key strategy in ensuring energy resilience and economic security for cooks both across sub-Saharan Africa and the rest of the world [53–55]. In Kenya, participants had specific fuel and appliance preferences for specific food types - for example, githeri, a mixture of maize and beans, is often cooked on a traditional wood fuel fire as it has long cooking times, needs a slower heat, and participants felt more comfortable walking away from the wood fuel fire than the biogas system. This means that depending on which fuels and appliances are stacked together, choices may be made to underuse the available biogas, resulting in an increased chance of venting occurring. Interestingly, users did not want to swap cooking technologies during the process of cooking githeri if they perceived there was not enough gas pressure to cook the entire dish then firewood would be chosen. This was especially the case in smaller biogas digesters, where unless the cook was certain that there would be enough gas to complete the cooking process, the cook would choose another technology.

3.1.2.5. Lack of market access for users & owners. As with all technological solutions, technical failures are a component of running an AD system as the hydrogen sulphide component of biogas can be particularly corrosive to pipes, fittings, and stoves - this is especially relevant for users who do not have or have a broken "desulphuriser". When these components fail, not only do they cause significant leaking, but users also stop using their systems. In Kenya, there is a centralised market for biogas components which is based in Nairobi thus the time to get replacement parts is significant, as one participant stated - "*Cooking stoves aren't available in Meru not unless you go to Nairobi*" (*K-Me-3*). This can additionally result in users purchasing stoves that are not meant for biogas use, say an LPG stove, and crudely modifying it for purpose. These modified stoves are inefficient and often dangerous to users due to leaking and, further compounding the problem, faster failing components due to minimal corrosive resistance - "*I have two burners. In the main kitchen I use the biogas double burner where I do most of my cooking needs. With the outside kitchen I have the LPG converted standing burner, but I rarely use it because it has some problems with ignition*" (*K-Me-1*).

3.1.2.6. A lack of training on maintenance and venting. A lack of maintenance leads to issues such as lower pressures at the stove due to water blockage - "*I have experienced challenges with low pressure due to water traps not being opened since my husband forgot to open the water point so that water in the pipeline can be emptied*" (K-Mu-5). This will increase the rate of venting as cooks will not cook with the gas if they see a problem, despite the biogas production being continuous.

This makes the case for continuous training for owners and operators. However, training to help mitigate practices that are associated with potentially increasing venting sits under the unknown unknowns category for users as there is so little understanding of the phenomenon. Users stated that they were interested in how they can more effectively use their gas and digestate to further optimise their systems - especially in cases where the owners and operators of the systems are different, "*I would like to be trained so that I will be able to train my people even after changing them now and then*" (K-Me-2). Essentially participants were interested in training that helps them extract more value out of their systems, this could be around optimising gas/digestate production, the post-processing of digestate (into other fertilisers or animal feeds), or ways to utilise excess gas (and accompanying appliances). This training must be accompanied by adequate supply-side market creation and awareness activities. For example, the participants who were part of farmers' groups (through ABPL) had a much better understanding of the operation and maintenance of their plants - a number even mentioned that the releasing gas from within the digester was harmful to the environment.

3.2. Exploring supply-side drivers: supplier equipment sizing and design

Demand side drivers, especially around user-behaviour are only one dimension of venting drivers. Both the supply, and system (as explored in the next section), make a significant contribution to this phenomenon. We often see users chastised for the failure and abandonment of their biogas system, which is deeply problematic, especially in cases where the failure of these units results in backsliding to unhealthy and polluting fuels [54,56]. Private sector actors, such as energy services and systems providers, may be equally responsible for bringing about the reality of venting. In this section we identify two key supply-side drivers which significantly affect the venting phenomenon, these are: digester sizing (from the user perspective) and sales practices of biogas manufacturers and builders. In both cases, inadequate digester sizing (either through poor sizing advice or sales practices) leads to venting through the underuse of gas.

3.2.1. Digester sizing (from the user perspective)

When asked the question - **why did you choose to construct this size of digester?** - farmers gave a range of answers that were based on past experiences and the socio-cultural, environmental, and financial constraints. First, past experiences; this was influenced by friends and family members with functional or undersized biogas units, "*The size, I had seen how my dad's biogas had low pressure since it was a small size biogas and hence, I was categorical that I would go for a bigger size*" (*K-Em-3*). Second, the socio-cultural, environmental, and financial constraints of users/owners; these factors range from the physical space available for digestion, the position of digester,[3] the cost of the system, the farmers own knowledge on what are the different size systems and their benefits, and the age of the user (smaller systems were perceived as more manageable by participants). Finally, several farmers stated that they didn't have a choice in their digester size due to the preassigned constraints of donor-funded biogas projects, "*You know this was a donor funded project, and it was specific on this size of the biogas. There was no choice*" (*K-Em-4*). Unfortunately, these top-down models of development still exist and have a significant impact on the optimisation of biogas systems - often these preassigned sizes do not meet the real, and evolving, energy needs of the users and hence miss-sized units cause venting through the underuse of gas.

[3] Although further away from the house is perceived to need a larger digester, the inverse is actually true. Whereby a large digester that will be more often not full of gas will exert less gas pressure than a small digester with the same amount of gas stored.

3.2.2. Sales practices around digester size

The critical learning from this process of data collection in Kenya revolved around the sales practices that are used to size biogas units. A number of participants stated that their biogas systems were sold based upon the available feedstock rather than gas demand. As an example, Fig. 4 shows data for sizing biogas plants based on both gas usage and available feedstock (cows), however, it is far easier for the salesperson to assess the number of cows rather than the less tangible m^3 of gas demand. Indeed, gas production is abstract unless related to what that means practically e.g. suitable for a family of 6 with a specific number of appliances. Whilst the sizing of digesters based on available feedstock simplifies practices for biogas technicians, this can lead to oversizing practices. As presented in Chaney et al. [43] and Chaney et al. [31], oversized units are more likely to vent. A balance of the two approaches, where sales practices revolve around both the available feedstock and potential gas usage, is needed to minimise venting.

> "*I have always had plenty of cows, because I was told that if I have two cows, the project can start*"
>
> (*K-Em-2*)

> "*Actually, I don't know* [*why that size was chosen*]*, the person who came to install for told me that will be enough because I had five cows*"
>
> (K-Me-3)

3.3. Exploring systemic drivers: venting in the dark

As with any technologically led sector, which tends to focus only on the techno-economic, there is often an underappreciation of the effects of the wider system on the sustainability of the technological solution. In this section we look to identify the systemic drivers which have resulted in a lack of understanding around venting.

3.3.1. Systemic drivers of the lack of understanding of venting

3.3.1.1. Perception that household-scale digesters do not pose a significant climate threat. The venting household-scale biogas systems are a significantly under-explored phenomenon. Those who have explored this topic area have done so with larger scale and commercial biogas digesters in Europe or the USA [26] which are not used directly for cooking - typically these are well optimised biogas digesters with significant commercial implications if they are losing valuable biogas. This research, which provides the basis for the "loss" estimations (which do not distinguish between venting and leaking) in the current carbon credit methodologies, was conducted far away from sub-Saharan biogas context - different quality standards, different climates, different socio-cultural cooking patterns, and different use cases. Yet, these numbers were readily accepted. In addition, and possibly why these socio-culturally disconnected statistics were unquestionably accepted, there is a wide scale perception that household scale biogas digesters do not pose a significant climate threat due to their limited physical numbers and perceived climate good through the offsetting of more polluting fuels such as firewood and charcoal [58]. Estimations around the number of household scale biogas units globally are, as of 2019, 50 million [4]. If the results of Chaney et al. [31] are extrapolated across this group, on average 14 % venting 25 % of the time (with 7 % venting 40 % of the time), then this represents a significant proportion of global methane emissions. This triple assumption - units are optimised (and minimised venting), there are a small number, and they have limited climate impacts - has led to a systemic under exploration of this phenomenon.

3.3.1.2. Lack of technical solutions which can quantify venting. The lack of awareness of the venting phenomenon results in a significant technological gap of monitoring devices which are designed to understand this phenomenon – in fact, there is only one such device which can monitor venting in real time (the Inclusive Energy Smart Biogas meter [39]). This is in contrast to other energy sectors such as solar where metering is a critical component of the technical system and its accompanying delivery model [59] - the biogas digester functions whether it is monitored or not. The lack of affordable technical solutions means that it was not cost effective to monitor hundreds or thousands of household-scale digesters thus the un-appropriate testing away from the context was the best option for determining venting rates as outlined in the existing literature base [24–26].

Dairy cows

Warm climate (>23° C) Model	Manure (L/day)	Number of cows (fully confined)	Biogas production: Daily biogas production (m^3/d)*	Biogas production: Daily average cooking time on one burner (h/day)**	Biogas production: Equivalent in LPG (kg/month)	Biofertilizer production (L/day)	Biofertilizer production (ha/year)
Sistema 6	45	2	1.7	3.3	21	135	4.9
Sistema 8	65	3	2.4	4.8	31	195	7.1
Sistema 12	90	5	3.3	6.7	43	270	9.9
Sistema 16	130	7	4.8	9.6	62	390	14.2
Sistema 20	180	9	6.7	13.3	86	540	19.7
Sistema 30	260	13	9.6	19.2	124	780	28.5
Sistema 40	350	18	12.9	25.9	166	1050	38.3
Sistema 80	700	35	25.9	51.8	333	2100	76.7
Sistema 120	1050	53	38.8	77.7	499	3150	115.0
Sistema 160	1400	70	51.8	103.5	665	4200	153.3
Sistema 200	1750	88	64.7	129.4	831	5250	191.6

* The biogas production is estimated based on a standard biodigester use.
** The production of biogas is variable and depends on particular farm's operating conditions.
NOTE: a waste: dilution water ratio of 1:2 has been selected for cow manure.

Fig. 4. An example of sales practices - sizing guide from sistema bio. product catalogue for Kenya [57].

3.3.1.3. Opening Pandora's box. Whilst the drivers above outline the primary systemic barriers around the lack of focus on venting, when overcome, these barriers also act as the entrance point to a Pandora's box of resulting impacts. These impacts include, directly highlighting:

- Differences in venting between different types of biogas units, which due to the market-based nature of biogas programs, provide technology-agnostic funders with additional challenges in market dynamics.
- Differences in venting patterns for local, regional, and national contexts resulting in further targeting biogas programs to contextual needs. This additional work in contextual alignment increases the cost of programs and decreases the expected impact for donors.
- The inefficiency of biogas appliances, especially biogas stoves, and their need for further development (which would most probably be the burden of the private sectors) to meet the needs of the sector which is quickly moving towards the productive use of biogas and larger scale biodigesters.
- The inadequacy of existing verified carbon credit methodologies around venting and the significant possibility that biogas digesters are being incorrectly credited (both under and over credited, depending on the level of digester optimisation). This impact has the potential to further reinforce the transparency and accountability challenges of the carbon sector [56,60].

Once Pandora's box has been opened and the newfound knowledge disseminated it's critical that academic, practitioners, and policy makers act in accordance with what is best for the users of these technologies - in this case farmers across East Africa. If not, this irresponsible and uncritical acceptance of technological approaches driven by international actors has a significant impact on just and inclusive pathways to the completion of SDG7.

4. Discussion & synthesis – actions and a theoretical framework

The findings section presented the lived experiences of Kenyan farmers around the venting phenomenon across three dimensions - the demand, supply, and systemic. This approach enables each element of the Kenya biogas system to be addressed as part of a holistic approach to minimising venting. From both the farmers' own experiences and key literature, in this section we present first actions to minimise venting across the supply, demand and systemic-sides, then synthesise this data to produce a theoretic framework to connect the lived experience of farmers with pathways to minimise venting.

4.1. Actions to minimise venting across the supply, demand, and systemic

4.1.1. Demand-side actions

We propose four actions on the demand-side - direct use of extra gas, leveraging potential community and social capital by giving away or selling extra gas, extra gas storage, botting biogas, and optimised user behaviours (such as feeding rate and schedule) – and critically analyse them for potential effectiveness.

First, the **direct use of extra gas**. Participants were asked - **What might you do with this extra gas?** - User generated suggestions included, reducing electricity costs - through lighting, chaff cutter, brooders etc., and reducing other fuel costs - sterilising farming utensils and boiling water for hot showers. However, ABPL was quick to balance the benefits of these other technologies, especially around lighting:

> "*You said you would like to have a biogas lamp installed. I agree they do exist, but they are not efficient enough* [*and*] *maintenance cost is very high* […] *We do encourage you to install solar panels instead of biogas lamps since they are cheap to maintain*"
>
> - ABPL County Coordinator

There was a consensus that exploring ways of farmers directly using this gas themselves was the preferential method to decrease the venting rates and thus optimise the biogas systems.

Second, leveraging **community and Social Capital**. Participants also stated that they would share the gas (and digestate) free of cost with their neighbours who are an integral part of their community. Whilst there would be the potential to sell this excess gas, farmers were hesitant. This contrasts with farmers who sell the firewood collected on their own land that they have displaced by using the biogas system. There seemed to be a discrepancy between the market logic promoted by many biogas programs and the prevailing ethos of solidarity and sharing in Kenya. People were more interested in community building than in leveraging social capital for financial gain.

> "*But if the digester was big, I could even be sharing the gas with my neighbours.*"
>
> (*K-Em-4*)

Farmers were marginally more comfortable selling the digestate, possibly due to its link with agricultural productivity. One participant actively generated revenue from the sale of digestate whilst the majority stated that they would give it away to help out a neighbour.

> "*I have not yet been asked by anyone* [*for digestate*] *and I have never thought that anyone would give or borrow but if anyone is in need I would gladly give*"
>
> (*K-Ny-2*)

Third, **constructing additional Storage for excess gas**. Whilst some participants shared a desire to store this extra gas (in a storage bag such as a biogas backpack) and use it at a later date - the increase of storage would typically not reduce the rate of venting if venting was consistent due to frequent underuse of gas. Storage in this case would only delay venting by the amount of time it took to fill the additional storage. When asked about upgrading their biogas systems to increase the capacity, the majority of participants wanted to increase the size of their biogas units in order to produce more gas and/or digestate - as above, this could be to share the gas with their families, sell the digestate to raise funds, or due to the perception that biogas is a free resource, decreasing costs on other fuels (which are becoming exponentially more expensive).

Fourth, a number of participants stated they would like to have a method of bottling biogas in cylinders, similar to their experiences with LPG. Twinomunuji et al. [61] explore the technical feasibility of biogas bottling across the African continent, in both improving the quality of gas (through biogas cleaning as explored in Wasajja et al. [62]) and the process of compression. They show the initial investment in equipment is large thus possibly only suited for contexts where biogas is produced on a large scale.

Finally, **the optimisation of the feeding regime through remote monitoring**. Remote monitoring data can help inform decision making around venting - identifying venting volume, time, and frequency. From this data, technicians can advise specific users on specific optimisation actions - for example, reducing daily feedstock volume, frequency of feeding, and modifying the time at which the digester is fed [39]. The recommendations of the technicians are dependent on specific findings received from the user whilst carrying out remote optimization intervention exercises as outlined by Pergetti [63]. However, whilst this data can be significantly helpful to the farmer, it requires the individual farmer to adopt the suggested specific changes which may be challenging if, one, the owner and operator of the system are different, and two, the person operating the system is not willing to overcome their negative experiences with the digester.

4.1.2. Supply-side actions

As with the demand-side drivers of venting, there are actions which

reduce venting driven by the supply-side. From the interviews conducted as part of this work, we identify two key areas - updating sales practices around digester sizing through technician training and appliance market creation and accessibility (to utilise this additional gas production).

First, **appliance market creation and accessibility**. Simply, full market development is needed to bring biogas appliances to users so that they can utilise excess gas (brooders, chaff cutters, generators). This would include supply-side activities such as creating a distributor network around Kenya (not only in Nairobi) and incentivising new organisations to enter into this market through tax reliefs, subsidies, and other financial incentives - as per the guidelines set by other market creation projects [64,65]. On the demand-side key activities could include, showcasing the appliances at relevant exhibition events, awareness raising with local media, and effectively training the households with installed devices for a better understanding of how the appliances function - this training is a critical component of increasing trust and confidence in the appliance markets for farmers.

Second, **expanding technician trainings**. There are many opportunities for technician training, especially around oversizing. This would include reinforcing the importance of detailed energy needs assessments, promoting tailored solutions rather than one size fits all (as often the case for donor-funded projects with short implementation timelines as outlined above), strengthening the operation and maintenance services, and specific training around venting and its drivers - preferably utilizing the functionality of technologies that can track venting in real time (through a remote monitoring device such as the Smart Biogas meter [39]).

4.1.3. Systemic-side actions: moving the needle on the systemic

Mitigating against these systemic drivers requires extending many of the demand and supply side mitigations into the systemic. For example, this means not only providing training to farmers, technicians, and biogas companies but also to the international biogas community

Table 3
A theoretical framework for minimising venting.

Factor	Sub-Factor	Relation to Venting	Potential for Venting	Mitigation Actions (Summary)
Demand-Side: User Awareness of Venting	Perceptions of Extra Gas	How users perceive the impact of extra gas and how does that affect their gas usage.	*Low Risk*	**Building Community & Social Capital** - When faced with the question of what people would do with the extra gas several participants state that they would share the gas (and digestate) with their neighbours, who are an integral part of their community. **Additional Gas Storage** - whilst not a solution for people who underutilised their gas, this may be a potential solution for situations where optimised digesters need surge gas for specific events and gatherings. **Optimising Feeding Regime** - through user Experimentation **Training** - users were interested in how they can more effectively use their gas and digestate to further optimise their systems. The participants who were part of farmers groups had a much better understanding of their plants. **Appliance Market Awareness**
	Underperformance and link to venting	Overfeeding reduces the space for gas production - resulting in less gas and more venting.	*Medium Risk*	
Demand-Side: User-Behaviours which effect venting	Pre-Processing of Feedstock	Reducing digester shock.	*Medium Risk*	
	Feeding Regime	Overfeeding, Underfeeding, Correct feeding with low gas usage (for digester size)	*High Risk*	
	Seasonal Influence	Temperature differences impacting gas/digestate production with no adjustment of feeding regime.	*Medium Risk*	
	Pressure	Preference for higher cooking pressures & perception of high-pressure causing failure in bag digesters.	*High Risk*	
	Stacking	Alternative fuels resulting in underutilisation of biogas.	*Medium Risk*	
	Lack of Maintenance	Water blocking pipes increases pressure.	*Low Risk*	
	Lack of Market Access	Long time for replacement parts, no way to utilise excess gas, resulting in use of modified (and this not certified) stoves.	*Low Risk*	
Supply Side: Supplier Equipment Sizing & Design	Choice of Digester Size	Based on past experiences, Socio-Cultural, Environmental, and Financial Constraints of Users/Owners	*High Risk*	**Updating Sales Practice** - with more of a focus on gas/digestate need and consumption (stepping away from top-down donor needs model) **Establishment of Farmer Groups** - to co-solve challenges. **Appliance Market Creation & Accessibility**
	Sales Practices of Biogas Technicians	Sizing biogas units from the number of animals, rather than the gas need. Lack of an appliance market.	*High Risk*	
	International Funder Requirements	Only installing one size of digester due to funder requirements which is then miss-sized.	*High Risk*	
Systemic Side: An Overlooked Phenomenon	Multi-Dimensional Impact of a better understanding of Venting	Potential to significantly impact carbon market (over/under crediting), regional differences in venting, highlighting the inefficiency of biogas appliances	*Medium Risk*	**Advocacy & Awareness -** in International Community **Technical Development -** of low-cost IoT Enables Monitoring Devices
	Minimising Venting	Perceptions that household-scale digester do not pose a significant climate threat in terms of methane emissions.	*High Risk*	
	Lack of Technical Solutions	Lack of monitoring devices that can identify and quantify venting	*Medium Risk*	

around advocacy and awareness of the venting phenomenon. It also requires open and transparent discussion with donors on how and what to fund, what to expect in terms of impact, and a coordinated long-term approach to widespread biogas dissemination with the appropriate structures (say remote monitored biogas units with real time venting accounting). This also requires further technical development of low cost IoT enabled monitoring devices that can act as the connection point between the entire system of stakeholders. More work is needed to understand how to engage and mitigate these systemic drivers, projects such as the [project name removed] are looking to move this needle forward.

4.2. Establishing a theoretical framework for minimising venting

The final element of this paper is to synthesise the qualitative data from the demand, supply, and systemic drivers of venting with the actions for reducing or mitigating venting. In addition to collating the findings of this paper, we have assigned an estimated potential venting risk to each sub-factor based upon our own extensive experience with biogas systems as shown in Table 3. For practitioners trying to understand the "low-hanging-fruit" for quickly optimising a biogas system, this table provides quick information on both the highest and lowest risk activities for venting - a low risk potential result in lower rates of venting, as opposed to high risk potential which has high rates of venting, These risk values have been cross-referenced with ongoing data analysis activities in the wider SB3 project. In future, this table can be weighed against a cost benefit analysis resulting in an effective decision tool for mitigating against venting at the lowest cost point for the program, biogas manufacturer, and ultimate users.

5. Conclusions

In this paper we aimed to understand, explore, and establish pathways to minimising venting in household scale biogas systems in Kenya. Through primary and secondary research - the qualitative interviews and the rapid review of household-scale biogas systems, user behaviour, and leaking and venting - we have established that venting is a significantly understudied phenomenon, and these household scale systems have the potential to make a significant contribution to global methane emissions.

Our findings highlight the drivers of venting from three perspectives - the demand, the supply, and the systemic. On the **demand side**, we identified current gas production (and its relationship to use) and whether this was appropriate for users' needs. Responses could be broadly classified into three categories; users who do not have enough gas to use for all their cooking needs (resulting in stacking of multiple cooking technologies based on biogas availability), users who only need to supplement their biogas for large events and family gatherings, and users who have enough gas for all their needs. Areas in which user-behaviour impacts venting included pre-processing feedstock, feeding regime, seasonal influence, pressure, cookstove stacking, lack of maintenance, and lack of market access. Potential mitigation to user-behaviour induced venting included the direct use of extra gas through additional biogas appliances, building community and social capital to share or sell gas, adding extra or additional storage of gas, optimising feed regime, and additional more general user training around optimisation of gas usage. On the **supply side** we often see users chastised for the failure and abandonment of their biogas system, which is deeply problematic. Digester sizing (from the user perspective) and sales practices of biogas manufacturers and builders were the two significant supply side drivers that were identified. One of the most significant learnings from this paper is that biogas units are typically sold based upon the available feedstock, rather than the potential gas needs of the customer. Whilst this simplifies practices for biogas technicians this can lead to oversizing practices which have a significant effect on venting. We suggest two key areas of improvement on the supply side - updating sales practices around digester sizing and further appliance market creation and awareness (to utilise this additional gas production). Next, We identify three systemic drivers; perceptions that household-scale digesters do not pose a significant climate threat, lack of technical solutions which can quantify venting, and the overwhelming Pandora's Box of impacts that result from a better understanding of the phenomenon. Many of these impacts have far reaching consequences, including changed market dynamics, under or overreporting of carbon offsets, the need to tailor venting mitigation (or optimisation) programs to specific country context and developing more efficient appliances. The findings section closes with the "venting framework". This is critical for practitioners trying to understand the "low-hanging-fruit" for quickly optimising a biogas system. In future, this table can be weighed against a cost benefit analysis resulting in an effective decision tool for mitigating against venting. Future work would include the testing and validation of this theoretic framework in a range of complex contextual settings in East Africa as well as the answering of many additional questions raised by this paper.

To conclude, this paper identifies many of the demand, supply, and systemic drivers of the under-studied phenomenon - venting. It is crucial that practitioners, academics, and policy makers not only directly address venting, but also act across the entire biogas ecosystem as part of the large-scale implementation of household scale biogas systems. The impacts of ignoring this phenomenon, and thus the voices of the users of these systems, not only have significant global climate implications but ultimately result in farmers across sub-Saharan Africa under-using their biogas systems and limiting their access to modern, reliable, and sustainable clean cooking fuel.

CRediT authorship contribution statement

Benjamin L. Robinson: Writing – original draft, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Mike J. Clifford:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Evance Okoth Ouma:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Kevin Kinusu Kinyangi:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Michael Wasonga Adimo:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Charles Njoroge Muchoki:** Writing – original draft, Project administration, Methodology, Data curation. **Grace Gathogo:** Methodology, Formal analysis, Data curation. **Leah Kendi Kithinji:** Methodology, Formal analysis, Data curation. **Tabitha Wanjiru Ngigi:** Methodology, Formal analysis, Data curation. **Teresiah Njeri Mbuguah:** Methodology, Formal analysis, Data curation. **Eric Murithi Rukaria:** Methodology, Formal analysis, Data curation. **Samuel Machui Mwangi:** Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] UNEP, Methane emissions are driving climate change, in: Here's How to Reduce Them, UNEP, 2021. http://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them (accessed February 14, 2024).

[2] E. Somanathan, R. Bluffstone, Biogas: clean energy access with low-cost mitigation of climate change, Environ. Resource Econ. 62 (2015) 265–277, https://doi.org/10.1007/s10640-015-9961-6.

[3] J. Wang, Decentralized biogas technology of anaerobic digestion and farm ecosystem: opportunities and challenges, Frontiers in Energy Research 2 (2014). https://www.frontiersin.org/articles/10.3389/fenrg.2014.00010 (accessed August 9, 2023).

[4] S. Jain, D. Newman, A. Nizhou, H. Dekker, P.L. Feuvre, H. Richter, F. Gobe, C. Morton, R. Thompson, Global Potential of Biogas, World Biogas Association, 2019. https://www.worldbiogasassociation.org/wp-content/uploads/2019/07/WBA-globalreport-56ppa4_digital.pdf (accessed September 18, 2024).

[5] M. Issahaku, N.S.A. Derkyi, F. Kemausuor, A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters, Heliyon 10 (2024) e24019, https://doi.org/10.1016/j.heliyon.2024.e24019.

[6] F. Lwiza, J. Mugisha, P.N. Walekhwa, J. Smith, B. Balana, Dis-adoption of household biogas technologies in Central Uganda, Energy Sustain. Dev. 37 (2017) 124–132, https://doi.org/10.1016/j.esd.2017.01.006.

[7] Yuwan Malakar, Chris Greiga, Elske van de Fliert, Resistance in rejecting solid fuels: beyond availability and adoption in the structural dominations of cooking practices in rural India, Energy Research & Social Science 46 (2018) 225–235, https://doi.org/10.1016/j.erss.2018.07.025.

[8] The World Bank, Tracking SDG7: The Energy Progress Report. https://trackingsdg7.esmap.org/data/files/download-documents/sdg7-report2023-full_report.pdf, 2023 (accessed October 2, 2023).

[9] N. Boyd Williams, R.S. Quilliam, B. Campbell, R. Ghatani, J. Dickie, Taboos, toilets and biogas: socio-technical pathways to acceptance of a sustainable household technology, Energy Research & Social Science 86 (2022) 102448, https://doi.org/10.1016/j.erss.2021.102448.

[10] J. Hewitt, M. Holden, B. Robinson, S. Jewitt, M. Clifford, Not quite cooking on gas: understanding biogas plant failure and abandonment in Northern Tanzania, Renew. Sustain. Energy Rev. 165 (2022) 112600.

[11] T. Nevzorova, V. Kutcherov, Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review, Energ. Strat. Rev. 26 (2019) 100414, https://doi.org/10.1016/j.esr.2019.100414.

[12] International Energy Agency, Global Methane Tracker 2023, IEA, 2023. https://www.iea.org/reports/global-methane-tracker-2023 (accessed February 14, 2024).

[13] UNFCCC, Methodological Tool - Project and Leakage Emissions From Anaerobic Digesters. https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-14-v2.pdf, 2017.

[14] E.G. Ullrich, E.R. Radtke, S. Chepkwony, K. Mwenja, Biogas Construction Manual: Theory Training on Biogas Plant Construction, GIZ Gmbh, Nairobi, 2011. https://openjicareport.jica.go.jp/pdf/12229423_03.pdf (accessed August 12, 2024).

[15] T. Al Seadi, D. Rutz, H. Prassl, M. Köttner, T. Finsterwalder, S. Volk, R. Janssen, Biogas Handbook, University of Southern Denmark Esbjerg, 2008. https://www.lemvigbiogas.com/BiogasHandbook.pdf (accessed July 23, 2024).

[16] Republic of Kenya Ministry of Energy & Petroleum, Sustainable Energy for All, Kenya Action Agenda: Pathways For Concerted Action Toward Sustainable Energy For All By 2030. https://www.se4all-africa.org/fileadmin/uploads/se4all/Documents/Country_AAs/Kenya_SE4ALL_AA_January_2016.pdf, 2015 (accessed August 29, 2024).

[17] Republic of Kenya Ministry of Energy & Petroleum, Sustainable Energy For All, Kenya Investment Prospectus: Pathways For Concerted Action Toward Sustainable Energy For All By 2030. https://www.se4all-africa.org/fileadmin/uploads/se4all/Documents/Country_IPs/Kenya_SE4All_IP_January_2016.pdf, 2015 (accessed August 29, 2024).

[18] Republic of Kenya, Energy Act. https://kenyalaw.org/kl/fileadmin/pdfdownloads/Acts/2019/EnergyAct_No.1of2019.PDF, 2019 (accessed August 29, 2024).

[19] Republic of Kenya Ministry of Energy, National Energy Policy. https://kplc.co.ke/img/full/BL4PdOqKtxFT_National%20Energy%20Policy%20October%20%202018.pdf, 2018 (accessed August 29, 2024).

[20] Republic of Kenya Ministry of Energy, Bioenergy Strategy 2020–2027. https://www.energy.go.ke/sites/default/files/KAWI/Other%20Downloads/Bioenergy-strategy-final-16112020sm.pdf, 2020.

[21] Republic of Kenya Ministry of Environment and Forestry, Kenya's Nationally Determined Contribution. https://unfccc.int/sites/default/files/NDC/2022-06/Kenya%27s%20First%20%20NDC%20%28updated%20version%29.pdf, 2020.

[22] ABPP, Evaluation of ABPP: Executive Summary. https://snv.org/assets/explore/download/evaluation_african_biogas_partnership_programme_executive_summary.pdf, 2019 (accessed December 16, 2021).

[23] SNV, Africa Biogas Component Project. https://snv.org/update/addressing-gaps-enabling-environment-small-and-medium-scale-biodigesters-kenya, 2023 (accessed February 6, 2023).

[24] J. Diaz Huerta, A. Bose, D.M. Wall, J.D. Murphy, R. O'Shea, Assessing the cost variability of emissions abatement in small-scale on-farm anaerobic digestion, DeCarbon 1 (2023) 100008, https://doi.org/10.1016/j.decarb.2023.100008.

[25] T.K. Flesch, R.L. Desjardins, D. Worth, Fugitive methane emissions from an agricultural biodigester, Biomass Bioenergy 35 (2011) 3927–3935, https://doi.org/10.1016/j.biombioe.2011.06.009.

[26] C. Scheutz, A.M. Fredenslund, Total methane emission rates and losses from 23 biogas plants, Waste Manag. 97 (2019) 38–46, https://doi.org/10.1016/j.wasman.2019.07.029.

[27] L. Mburu, Knowledge creation: an imperative for Africa's decolonization, Afroeconomics Law. https://www.afronomicslaw.org/2020/10/20/knowledge-creation-an-imperative-for-africas-decolonization, 2020 (accessed April 27, 2023).

[28] D. Moyo, Dead Aid: Why Aid is not Working and How There is Another Way for Africa, 2009.

[29] Gold Standard, Methodology for Animal Manure Management and Biogas Use for Thermal Energy Generation v1.1, 2023. https://globalgoals.goldstandard.org/433-ee-ics-methodology-for-animal-manure-management-and-biogas-use-for-thermal-energy-generation/ (accessed October 21, 2024).

[30] UNFCCC, Small-scale Methodology: Biogas/Biomass Thermal Applications for Households/Small Users. https://cdm.unfccc.int/UserManagement/FileStorage/4P06SGJCRLV2TME158U9HXWQ3OYIZB, 2022.

[31] J. Chaney, M. Clifford, B. Robinson, Measuring methane venting from household scale dome biogas digesters in Kenya and Uganda, Energy Sustain. Dev. (2025). Under final review.

[32] A.C. Tricco, J. Antony, W. Zarin, L. Strifler, M. Ghassemi, J. Ivory, L. Perrier, B. Hutton, D. Moher, S.E. Straus, A scoping review of rapid review methods, BMC Med. 13 (2015) 224, https://doi.org/10.1186/s12916-015-0465-6.

[33] C. Muller, H. Yan, Household Fuel Use in Developing Countries: Review of Theory and Evidence, 2018, https://doi.org/10.1016/J.ENECO.2018.01.024.

[34] J. Mwirigi, B.B. Balana, J. Mugisha, P. Walekhwa, R. Melamu, S. Nakami, P. Makenzi, Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: a review, Biomass Bioenergy 70 (2014) 17–25, https://doi.org/10.1016/j.biombioe.2014.02.018.

[35] G.V. Rupf, P.A. Bahri, K. de Boer, M.P. McHenry, Broadening the potential of biogas in Sub-Saharan Africa: an assessment of feasible technologies and feedstocks, Renew. Sustain. Energy Rev. 61 (2016) 556–571, https://doi.org/10.1016/j.rser.2016.04.023.

[36] Science Direct, Science, health and medical journals, full text articles and books. https://www.sciencedirect.com/, 2022.

[37] R. Ganann, D. Ciliska, H. Thomas, Expediting systematic reviews: methods and implications of rapid reviews, Implement. Sci. 5 (2010) 56, https://doi.org/10.1186/1748-5908-5-56.

[38] B.K. Sovacool, J. Axsen, S. Sorrella, Promoting novelty, rigor, and style in energy social science: towards codes of practice for appropriate methods and research design, Energy Research & Social Science 45 (2018) 12–42.

[39] B. Robinson, M. Clifford, G. Selby, Towards fair, just and equitable energy ecosystems through smart monitoring of household-scale biogas plants in Kenya, Energy Res. Soc. Sci. 98 (2023) 103007.

[40] B.L. Robinson, M.J. Clifford, J. Hewitt, S. Jewitt, Cooking for communities, children and cows: lessons learned from institutional cookstoves in Nepal, Energy Sustain. Dev. 66 (2022) 1–11, https://doi.org/10.1016/j.esd.2021.10.012.

[41] B.L. Robinson, M.J. Clifford, S. Jewitt, TIME to change: rethinking humanitarian energy access, Energy Res. Soc. Sci. 86 (2022) 102453, https://doi.org/10.1016/j.erss.2021.102453.

[42] B.L. Robinson, M.J. Clifford, S. Jewitt, Transforming North-South research partnerships: lessons learned from energy, technology & enterprise global challenge research fund projects, Energy Res. Soc. Sci. 93 (2022) 102837, https://doi.org/10.1016/j.erss.2022.102837.

[43] J. Chaney, M. Clifford, B. Robinson, Digesting data: improving the understanding of biogas use through remote sensing, Energy Sustain. Dev. (2025). Under final review.

[44] SNV, Household bio-digester installations in selected countries in Africa and Asia in 2021, SNV, 2022. https://a.storyblok.com/f/191310/b8ca144d18/snv-20biodigester-20status-20brief-20-28final-29.pdf (accessed August 23, 2023).

[45] N.K. Denzin, Y.S. Lincoln, in: Norman K. Denzin, Yvonna S. Lincoln (Eds.), The SAGE Handbook of Qualitative Research, 5th ed., SAGE, Thousand Oaks, Calif. London, 2018. Thousand Oaks, Calif. London.

[46] N. Mack, C. Woodsong, K.M. Macqueen, G. Guest, E. Namey, Qualitative Research Methods: A Data Collector's Field Guide, US AID, 2005.

[47] L.T. Smith, Decolonizing Methodologies: Research and Indigenous Peoples, Otago University Press, 2012. https://books.google.de/books?id=41rYMgEACAAJ.

[48] Practical Action, PMSD Toolkit, Practical Action. https://practicalaction.org/pmsd-toolkit/, 2023 (accessed May 4, 2023).

[49] Y. Liu, Q. Li, M. Dzakpasu, R. Chen, Y.-Y. Li, Re-evaluating the impact of feeding shock on anaerobic co-digestion of food waste and waste activated sludge: trade-off between efficiency and stability, Chem. Eng. J. 484 (2024) 149476, https://doi.org/10.1016/j.cej.2024.149476.

[50] I. Ferrer, S. Ponsá, F. Vázquez, X. Font, Increasing biogas production by thermal (70°C) sludge pre-treatment prior to thermophilic anaerobic digestion, Biochem. Eng. J. 42 (2008) 186–192, https://doi.org/10.1016/j.bej.2008.06.020.

[51] A. Gonzalez, A.T.W.M. Hendriks, J.B. van Lier, M. de Kreuk, Pre-treatments to enhance the biodegradability of waste activated sludge: elucidating the rate limiting step, Biotechnol. Adv. 36 (2018) 1434–1469, https://doi.org/10.1016/j.biotechadv.2018.06.001.

[52] N. Hamzawi, K.J. Kennedy, D.D. McLean, Anaerobic digestion of co-mingled municipal solid waste and sewage sludge, Water Sci. Technol. 38 (1998) 127–132, https://doi.org/10.1016/S0273-1223(98)00438-7.
[53] I. Ruiz-Mercado, O. Masera, Patterns of stove use in the context of fuel–device stacking: rationale and implications, EcoHealth 12 (2015) 42–56, https://doi.org/10.1007/s10393-015-1009-4.
[54] S. Jewitt, P. Atagher, M. Clifford, "We cannot stop cooking": stove stacking, seasonality and the risky practices of household cookstove transitions in Nigeria, Energy Res. Soc. Sci. 61 (2020).
[55] C.A. Ochieng, Y. Zhang, J.K. Nyabwa, D.I. Otieno, C. Spillane, Household perspectives on cookstove and fuel stacking: a qualitative study in urban and rural Kenya, Energy Sustain. Dev. 59 (2020) 151–159, https://doi.org/10.1016/j.esd.2020.10.002.
[56] A. Gill-Wiehl, D.M. Kammen, B.K. Haya, Pervasive over-crediting from cookstove offset methodologies, Nature Sustainability 7 (2024) 191–202, https://doi.org/10.1038/s41893-023-01259-6.
[57] Systema Bio, Product Catalogue - Kenya. https://sistema.bio/wp-content/uploads/1903_KENYA_CATALOG_LQ.pdf, 2024 (accessed July 10, 2024).
[58] S. Bruun, L.S. Jensen, V.T. Khanh Vu, S. Sommer, Small-scale household biogas digesters: an option for global warming mitigation or a potential climate bomb? Renew. Sustain. Energy Rev. 33 (2014) 736–741, https://doi.org/10.1016/j.rser.2014.02.033.
[59] R. Bellanca, B. Garside, An Approach to Designing Energy Delivery Models that Work for People Living in Poverty, Iied. https://www.iied.org/sites/default/files/pdfs/migrate/16551IIED.pdf, 2014.
[60] M. Little, A. Richter, A. Eales, Z. Müller-Karpe, A review of the standards, methodologies, technical needs and available resources related to digital monitoring, reporting and verification for modern cooking devices in the context of carbon finance, in: Modern Energy Cooking Services Programme, Loughborough University, 2023. https://mecs.org.uk/wp-content/uploads/2024/03/MECS-MMECD-Report-v7-FINAL.pdf (accessed September 11, 2024).
[61] E. Twinomunuji, F. Kemausuor, M. Black, A. Roy, R.O.J. Sadhukhan, R. Murphy, P. M. Leach, The Potential for Bottled Biogas for Clean Cooking in Africa, 2020.
[62] H. Wasajja, R.E.F. Lindeboom, J.B. van Lier, P.V. Aravind, Techno-economic review of biogas cleaning technologies for small scale off-grid solid oxide fuel cell applications, Fuel Process. Technol. 197 (2020) 106215, https://doi.org/10.1016/j.fuproc.2019.106215.
[63] S. Pergetti, Monitoring for impact: the case for a digital approach to biodigester performance optimisation, Inclusive Energy (2024).
[64] H. Clemens, R. Bailis, A. Nyambane, V. Ndung'u, Africa Biogas Partnership Program: a review of clean cooking implementation through market development in East Africa, Energy Sustain. Dev. 46 (2018) 23–31, https://doi.org/10.1016/j.esd.2018.05.012.
[65] G. Bensch, J. Kluve, J. Stöterau, The market-based dissemination of energy-access technologies as a business model for rural entrepreneurs: evidence from Kenya, Resour. Energy Econ. 66 (2021) 101248, https://doi.org/10.1016/j.reseneeco.2021.101248.